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An investigation into the behaviour of air rifle pellets in ballistic gel and their interaction with bone

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ABSTRACT

Although air weapons are considerably lower in power than other firearms, there is increasing concern that serious injuries can result from their misuse. The present study was therefore carried out to improve understanding of the terminal ballistic behaviour of air rifle pellets. Pellets were fired into ballistic gel under a variety of conditions.

The pellets penetrated further than anticipated from their low cross-sectional density, and Bloom number was not necessarily a good guide to gel behaviour. Pellet penetration into the gel decreased with increasing gel concentration, and appeared to be linear at higher concentrations. Pointed pellets penetrated up to 50% further than rounded pellets. Power and range affect penetration, but other factors are also important, and power alone is not a simple guide to potential penetration.

Test firings were also carried out firing pellets into ballistic gel that contained sections of animal bone. Computed tomography (CT) and visual observation were employed to record the interactions. CT scanning showed potential as a tool for examining pellet damage. The bone appeared to be undamaged, but the pellets were severely deformed on impact. If the pellet strikes the bone at an angle, less energy is absorbed by the impact and the pellet fragments may ricochet and cause further damage in the gel. A tentative model is proposed for estimating the energy absorbed by the impact.

1. Introduction

The regulation of firearms varies from country to country, for example within the United Kingdom a distinction is drawn whereby air rifles may be exempt from licensing provided they deliver <16.3 J at the muzzle, or 8.1 J in the case of an air pistol [1]. This distinction is partly based on the potential injuries that may be caused. Research on firearms has therefore concentrated on higher power weapons such as rifles, shotguns and handguns. Manufacturers tend to focus on improved weapon design or on bullet development for enhanced effectiveness. Usually this involves a combination of aerodynamic shape and ability to deform on impact. Gun club members often have a technical interest and may carry out chronograph tests and test firings into ballistic gel to improve performance when hunting, and a number of websites have grown up for exchanging practical knowledge.

From a forensic perspective most work has concentrated on techniques to show unique features linking a particular weapon to a scene, or on pathological factors and the nature of injuries, or injury patterns caused by firearms. To compare test firings for weapon identification, it is standard practice to fire the test bullet into cotton wool, water, or ballistic gel. The use of ballistic gel is also frequently used to simulate human tissue for these studies, and it is well documented how results can vary unless the gel production is strictly controlled [2,3].

In comparison, very little work has been carried out on air rifle pellets. Shotgun pellets have been examined due to the pattern formed as they spread out and the consequent damage caused, but the behaviour of these pellets cannot be directly related to the single pellet from air weapons. A study by Dahlstrom et al. [4] looked at the penetration of shotgun shot into ordnance gelatin, ordnance gelatin covered with clothing, and ordnance gelatin embedded with a rib bone at various distances from the target. The results from this study show that the larger the pellet size the greater the deformation of the pellet, and as the firing range increased the pellet deformation decreased. X-rays were used to determine the presence and size of any shot that was stopped by the rib and the clothing, although little information was provided as to the damage of the rib or how they determined the shot deformation. Another study carried out by Kneubuehl and Thali [5] aimed to find out if a synthetic bone would accurately simulate a human bone structure. They used a swine bone, also mounted in gelatin, for comparison with the synthetic bone of the damage caused by a gunshot. The results showed that behaviour was similar between the two bones.

The rationale for focussing research on more powerful weapons is obvious – they create more damage and can be lethal. The

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perceived wisdom has been that airguns are less hazardous because the projectile has much lower energy: 16.3 J compared with 100–600 J for handguns, and 1000–3500 J as a typical range for rifles. However, within the UK most firearms offences are by air weapons [6,7] although the majority of these are lesser offences such as vandalism, and minor assault. It has also been reported that in the USA an estimated 30 000 patients attended emergency rooms with airgun injuries in the period 1992–1993 [8].

There is debate about the seriousness of airgun injuries and airgun wounds are sometimes treated as innocuous injuries [9]. However other studies have shown that injuries from airguns can be more serious and in some instances potentially life threatening [10]. Although rare, deaths have occurred through their use or misuse [11,12] and in a 12-month period three separate and unlinked cases were reported where children received airgun pellet shots to the chest [13]. At least 35 deaths due to air gun discharge have been recorded in the medical literature [8] and the news media record other instances of fatalities from air weapons. There is therefore increasing concern over accidental death from air rifles due to peculiar circumstances such as age of the person, or location of the impact, and there are various campaigns to further prohibit the sale and use of air weapons.

Damage to tissue is sometimes looked at in terms of the local dissipation of kinetic energy [14] though this is disputed and it may be more appropriate to examine how the penetrating projectile disrupts the tissue. Fackler [15] discusses the misunderstandings about penetrating projectile wounds that are related to the least lethal injuries and to uncomplicated extremity wounds. These, however, are the types of wounds commonly encountered through the damage caused by airguns.

In order to try and develop further understanding of the behaviour of air pellets, and their potential to cause injury, this study was carried out and has concentrated on the pellet behaviour rather than wound simulation.

2. Methodology

Although considerable work has been done on the use of ballistic gels, there can still be variations within the methods used [2,3]. For the initial part of this investigation, it was decided to investigate variations in the gel for use with air rifle pellets. With lower energy, the gel penetration was expected to be less, and it was anticipated that it might be necessary to use a reduced strength gel in order to give a reasonable depth of penetration for measuring.

Two methods of gel preparation were used but the basic method employed was that described by Jussila [2] with modification in the scale of preparation. The gel powder was mixed with cold water initially to hydrate it and hot water was then added. In the alternative method the initial mixing was done with hot water (55 °C) and cinnamon oil was added as preservative. Some sources suggest that temperatures above 40 °C can affect the physical properties ([3], citing work by Fackler) whereas other sources dispute this and argue that solubility in hot solution is preferable [2].

The chemical and physical properties of three of the gels were measured at 6.7% gel powder by weight, the manufacturer's recommended concentration to achieve 250 Bloom. The fourth gel was food grade material from non-animal sources and claimed to achieve 250 Bloom at 1.5% concentration. Each gel was tested for: moisture, ash, opacity, pH, Bloom strength and viscosity. These different gelatin powders were examined in firing tests at different concentrations from 5 to 30% gel powder.

Gel was cast into different shape containers to see whether comparative results could be obtained. Initially plastic knife blade holders (similar to a measuring cylinder) were used. In this case the restraining effect of the walls would prevent expansion of the gel and increase resistance on the pellet. Consistent results were obtained, although they cannot be directly correlated with alternative gel configurations. It has previously been noted [16] that even standing gel blocks on a surface will have a restraining effect on gel behaviour.

In the second series the same procedure was used but the gel was cast into blocks in 3 l plastic containers with dimensions 180 mm × 260 mm × 75 mm or 170 mm × 255 mm × 85 mm. The gel was stored in a refrigerator and removed just before taking to the firing range. These blocks are of different dimensions compared with conventional firings due to the lower power involved.

In the first phase, four different air rifles were used (Westlake, Air Arms, Weihrauch and BSA rifles) to examine different powered weapons. The firing was chronographed to determine velocity and hence kinetic energy. In the second phase a 0.22 calibre Diana RWS 48/52 rifle was used and three different pellets were investigated. A third variable examined was firing distance from the gel and 5, 10 and 15 m were used.

In the third phase of the study, all gels were cast using 10% of 250 Bloom ballistic gelatin in hot water and casting into 3 l plastic containers. A femur from a cow was obtained and was thoroughly cleaned and sterilised before being sectioned into 4 cm lengths by hacksaw. The bone was placed in the predetermined position to give the required depth within the gel. As the bone had a relatively flat face this was positioned at a predetermined angle to the line of firing before adding the gel. After pouring, the gel was stored in a refrigerator and removed just before being taken to the firing range.

In this series of tests the femur samples were placed at 5, 10, 20, 30, and 40 mm from the front face of the gel. The femur face was inclined at an angle of 0, 25, 50 and 75° to the firing line. Sample firings of pellets were chronographed, and the gels were examined visually after each firing. For each test the penetration of the pellet into the gel was measured using a ruler. The gel was photographed and any observations were recorded. Bone and pellets were removed from the gel, washed, dried, observed and photographed.

In the case of 15 of the bone samples in the gel, the specimen was taken for examination by computed tomography (CT) scanning before removing the bone from the gel. CT scanning uses X-rays to take a series of 2D image 'slices' through the object and these are combined by computer to produce a 3D image. By varying the sensitivity of the measurements it is possible to selectively remove materials with different opacity to X-rays, allowing the bone and pellets to be viewed, or the pellets on their own.

There are, however, two problems with CT scanning. Firstly, scan speed affects the image resolution and a compromise needs to be reached. In this study fast scans (20 min) were taken of the bone before firing, and slow scans (80 min) of the bone after firing. Secondly, the files generated were very large (20 GB) and storage presented a problem. In practice, the 3D image was rotated and examined, and a jpeg image of any special features was saved.

3. Results and discussion

3.1. Gel properties

Most authors propose the use of 10% gel, although some papers suggest higher values such as 20% gel, for example, Harbey, Berlin, and Ragdale cited by Jussila [2] and Amato, Celens, Korac and NATO cited by Nicholas et al. [3]. In the first phase of this study 10% gels did not give acceptable stopping distances and 20% was normally used in later tests. Jussila [2] examined steel ball bearings with a cross-sectional density (mass in grams divided by the square of the diameter in centimeters) of 2.4 in his calibration of gels. The cross-sectional density of the pellets used in the present study is comparable (2.8–3.5), although both are much lower than bullets (e.g. 8.0 for a 0.22 LR). The pellets were expected to have penetration comparable with Jussila's values (typically 45–96 mm depending on velocity) but the actual penetration observed in the present study was greater than expected and exceeded the dimensions of the gel. An extended investigation of gel properties was therefore carried out.

The measured gel properties (Table 1) all fell within their manufacturers specification apart from the gel Bloom strength.

Table 1
Physical and chemical properties of the gelatins used.

	Gel strength (Bloom)	Viscosity (mPas)	pH	Clarity (%)	Moisture content (%)	Ash content (%)
Gel 1 Gelita brand ordnance gelatin	122.5	5.07	5.09	90.0	10.92	0.29
Gel 2 Sigma–Aldrich brand ordnance gelatin	119.0	5.40	5.14	88.3	11.17	0.22
Gel 3 1:1, Gelita: Sigma–Aldrich mix	118.5	5.46	5.12	88.1	11.01	0.27
Gel 4 ISP Texturese 720 (MT720)	256.5	1.26	9.01	85.7	0.48	78.37

Four of the gels recorded gel strengths approximately half of the predicted value, and only the non-animal gel recorded a strength close to 250 Bloom. This gel was significantly different in appearance and physical properties (Table 1). Paradoxically, this gel was the one that gave least resistance to pellets, despite its high measured Bloom number. (Bloom strength was measured by adding weights to a 12.5 mm diameter piston until it protruded 4 mm into the 162 mL sample of gel.)

Consistent results were obtained between different batches of gel and between different brands, suggesting that the preparation method was reproducible. It was unclear whether there was an unrecognised factor in the gel preparation that accounted for the greater penetration, or whether pellet behaviour in the gel is different to bullet behaviour.

3.2. Penetration of gel

Jussila [2] proposed acceptable penetration ranges for different velocities into 250 Bloom gel, and for steel ball bearings fired at 160 ms^{-1} it is 68–78 mm penetration. The air rifles were chronographed at 140–190 ms^{-1} and the knife blade holders were 160 mm long so it had been expected to be adequate, even though a gelatin powder used had a low Bloom number (120 Bloom). Although the penetration depth does depend on Bloom number, it is not a direct linear correlation and 120 Bloom did not give a major increase in penetration when compared with 250 Bloom gel using the lower power Westlake rifle. It was therefore expected that a doubling of gel length would be adequate to stop the pellets. However, the pellets retained sufficient energy to rebound off the plastic base and cause damage to the plastic base as seen in Fig. 1. This occurred even with higher gel concentrations. Clearly the gel has had little restraint on the pellet and the pellet retains a substantial part of its kinetic energy. The trajectories are approximately linear although one shot diverged in a yawing motion. In both cases the rebound from the plastic wall has been an elastic collision and it has followed the same path back, but the pellet has rotated by 180° so the tip is still leading. The pellet stopped within 1–3 pellet lengths and no additional gel damage was observed. There is no indication of continuing rotation or tumbling of the pellet on impact. This complete inversion is unexplained, and it is unclear whether a similar effect would be observed for a pellet striking bone as the physical properties of the bone will differ from those of the container. However, any similar effect would be likely to cause extended damage in soft tissues around the point of impact.

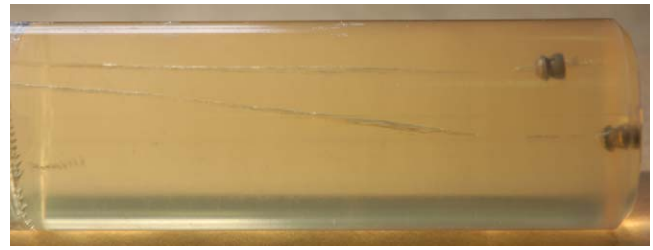

Fig. 1. Pellet track in ballistic gel.

3.3. Comparison of different gels

Fig. 2 compares three different gels (nominally 120, 250 and 260 Bloom) at two concentrations (10% and 20%) with two rifles (approximately 8.5 and 15.3 J) and two ranges (5 and 10 m). As may be expected, the more powerful weapon penetrated further, and the more concentrated gel reduced penetration. With the more powerful weapon and the more dilute gel in several trials the pellet was not stopped by the gel length of 180 mm.

As would be expected the Bloom value has an effect, but at 20% concentration and 8.3 J (Westlake rifle) there appears to be little difference in penetration between 120 Bloom, 250 Bloom and 260 Bloom gel powders. However, the differences are more pronounced at lower gel concentrations and with higher power rifles. Choice of gel, and test conditions, is therefore important for differentiation of pellet behaviour at lower power.

3.4. Effect of gel concentration

Fig. 3 shows results from the Webley Hustler pellets fired with the BSA rifle into 120 Bloom gel at different concentrations and this graph suggests a linear relationship between penetration and concentration above 15% gelatin concentration.

Over a range of firing conditions the 25% gel stopped all the pellets on average 24% (18.1 mm) shorter than its 20% gel at the same distance and the same power. The largest difference in penetration between the gelatin concentrations was 42% or 23 mm at 10 m range and 8.3 J whilst the smallest was still 12% or 11.5 mm at 5 m with 13.7 J. This suggests that the lower the impact energy the greater the differentiation in penetration, again suggesting that air rifle pellets require a different interpretation in test firings compared with firearms.

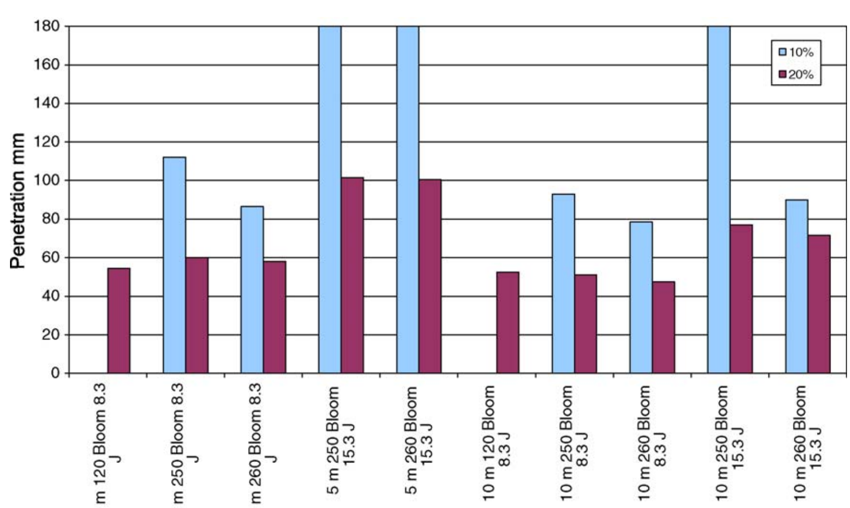

Fig. 2. Effect of gel concentration on penetration under various conditions.

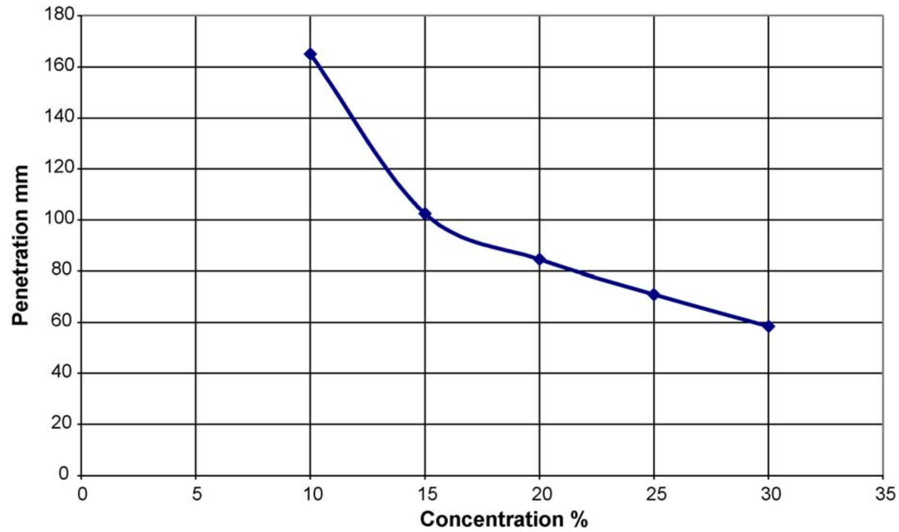

Fig. 3. Pellet penetration against gel concentration (120 Bloom, 5 m range, 13.7 J).

3.5. Variation in penetration with delivery power

The combinations of pellets and rifles can be seen in Table 2. There is a slight difference between the muzzle power for the pellets with the BSA Huntsman (pointed) being 5–10% greater than the Webley Harrier (rounded) and around 10% more powerful than the Webley Hustler, despite both being pointed pellets. The Hustler pellets are shorter and 20% lighter but only achieved a 5% increase in muzzle velocity and consequently have lower kinetic energy.

Table 2
Muzzle velocity and power for different air weapons with different pellets.

Rifle	Pellet	Pellet shape	Pellet mass (g)	Average velocity (m/s)	Power (J)
Westlake	Webley Harrier	Rounded	0.81	143	8.3
Westlake	BSA Huntsman	Pointed	1.02	130	8.5
BSA	Webley Hustler	Pointed	0.84	180	13.7
BSA	BSA Huntsman	Pointed	1.02	172	15.0
Weihrauch	Webley Harrier	Rounded	0.81	174	12.2
Weihrauch	BSA Huntsman	Pointed	1.02	168	14.2
Air Arms	Webley Harrier	Rounded	0.81	194	15.3
Air Arms	BSA Huntsman	Pointed	1.02	182	16.9

Fig. 4 shows examples of the effect of muzzle kinetic energy on penetration under different conditions of 5 and 10 m range, and gel concentrations of 10%, 20% and 25%. As kinetic energy reaches the UK legal limit for air rifles of 16.3 J the penetration is greater and its effects are potentially more devastating than those of an air pistol at its legal limit of 8.1 J. However, even at 8.3 J pellets penetrated 55–60 mm of 20% gel. It has been proposed that "a review of legislation should be considered for air weapons rather than setting a muzzle kinetic energy limit before a licence is required" [17], and these observations would tend to support that view.

3.6. Effect of pellet

Fig. 5 shows 250 Bloom gel at 5 m and demonstrates the effect of different pellets. In general the rounded pellets penetrated less deeply than pointed pellets by an average of 29% or 25 mm at 5 m

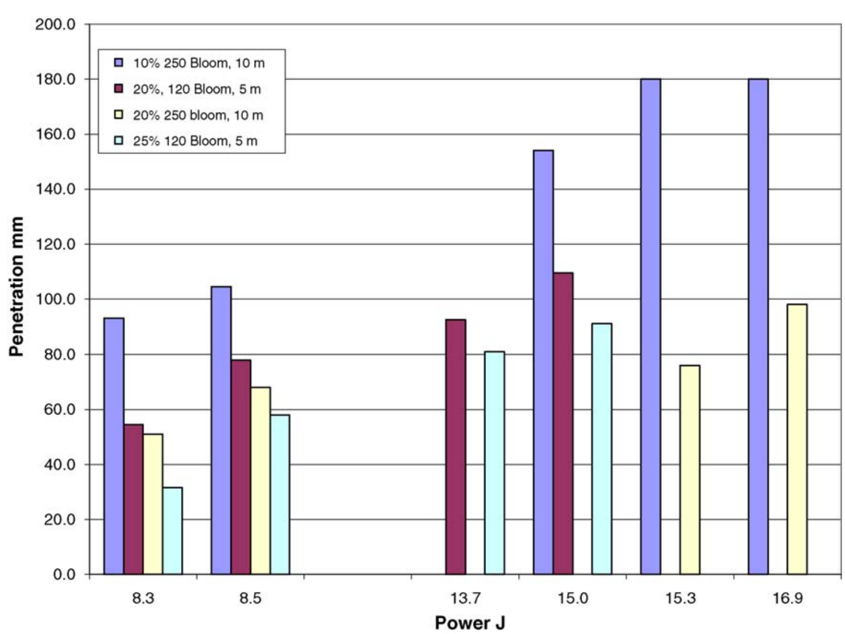

Fig. 4. Penetration at various muzzle powers.

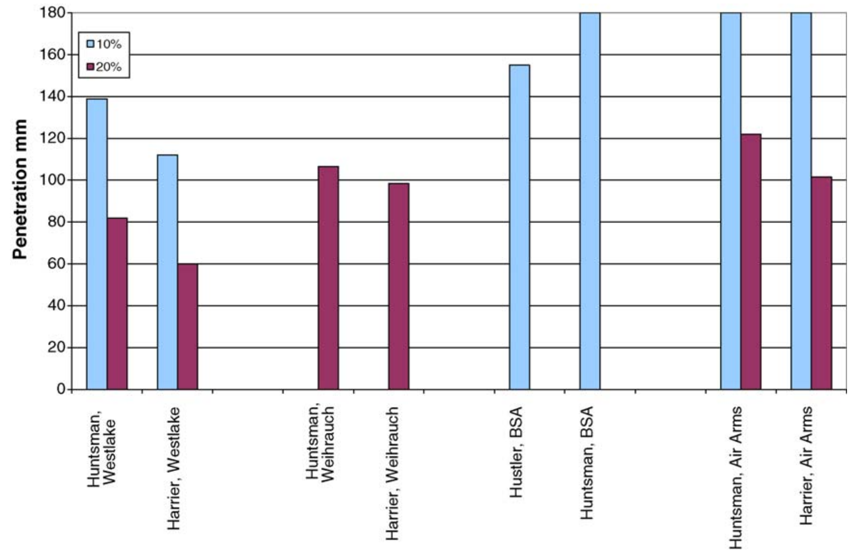

Fig. 5. Penetration of different pellets (250 Bloom, 5 m).

range and 27% or 20 mm at 10 m range. The variation due to firing range was 11% (11 mm) at 10 m range into 10% 250 Bloom gel, and 53% or 30 mm at 10 m range into 25% of 120 Bloom gel. As noted in the previous section, this means that power alone is not a suitable guide to potential penetration and injury.

3.7. Effect of firing range

Test firings under a range of conditions at 5 and 10 m range are compared in Fig. 6. Whilst there appears to be a greater effect on penetration with the pointed pellets (an average drop of 14 mm over all conditions) compared with the rounded pellets (average drop of 9 mm), these correspond to 15.3% and 13.3% reductions, respectively. Individual reductions ranged from 4% (120 Bloom at 20% concentration) to 25% (250 Bloom at 10% concentration).

3.8. Use of CT scanning

Whilst optical observation of firings into gel can be very useful, there is a problem with distortion of the image due to the opacity of the gel and the variations in refractive index. CT scanning allowed the generation of a 3D image that could subsequently be manipulated. Banno et al. [18] have used optical images to generate 3D images of bullets, but this requires transparent materials and may be hindered by changes in opacity in ballistic gel. The present technique was able to differentiate gel, bone and pellet. Further work is necessary to develop the technique but Figs. 7 and 8 indicate its potential. Fig. 7 shows pellet contact with the bone and the image was rotated to find the preferred viewing orientation. Fig. 8 uses a filter to remove the image of the bone and allows 3D imaging of the pellets and their fragments in situ.

3.9. Damage to bone by pellets

Optically, no damage could be observed on the bone and most of the CT Scans appear to show no evidence of density change in the bone due to compaction, although some CT scans may suggest some possibility of local damage. Fig. 7 shows an example. It is possible that this is not damage to the bone, but may be fragmentation or 'wipe' from the pellet. The bone used was a

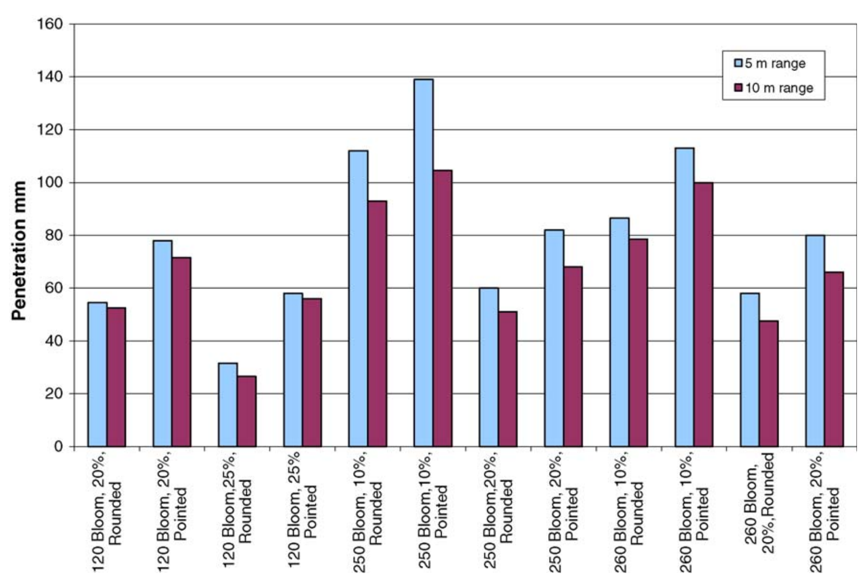

Fig. 6. Effect of range (Westlake rifle).

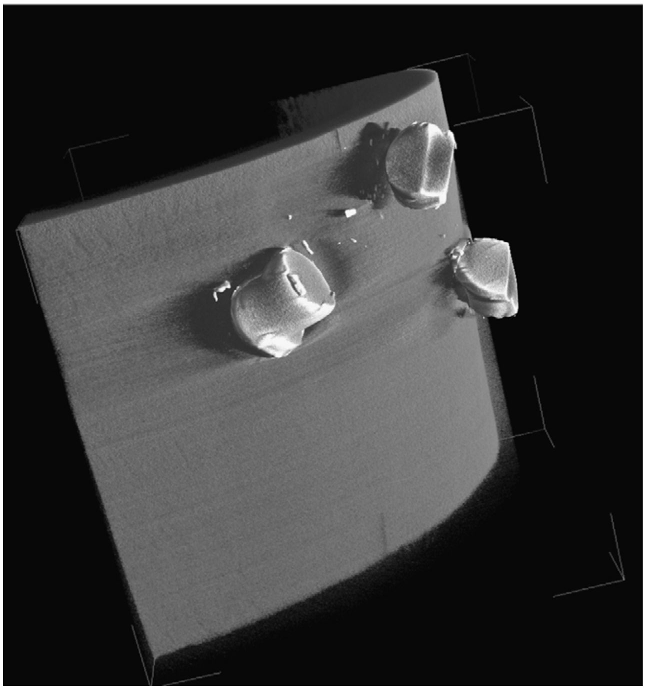

Fig. 7. CT scan of pellets and bone.

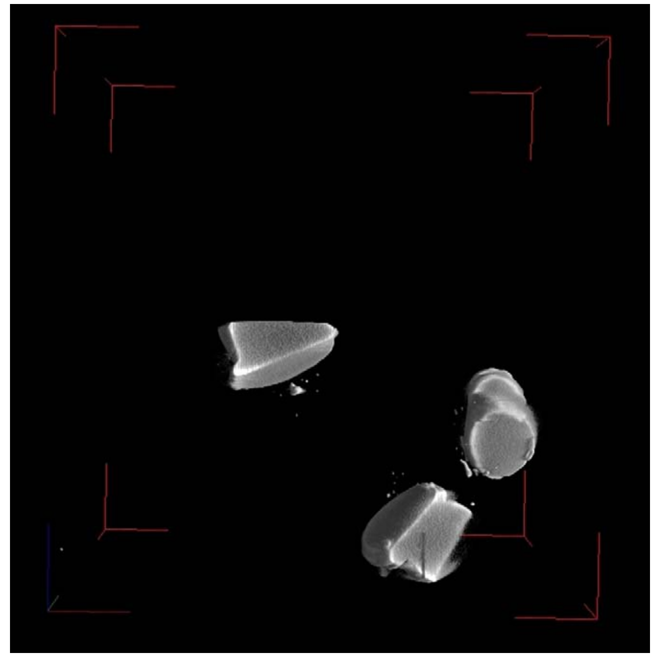

Fig. 8. CT scan of pellets with bone filtered out.

cow femur in order to present a reasonable sized target for the experiments and its physical strength may be expected to be high. Testing would be required with other types of bone to see whether any structural damage can occur. Use of other techniques such as scanning electron microscopy or atomic force microscopy may also indicate whether structural damage takes place.

3.10. Damage to pellets

Table 3 summarises data on shots fired at bone placed in ballistic gel.

3.10.1. Effect of bone depth in the gel

Pellets 1, 2, 8, and 3 were fired at bones mounted in gelatin at depths of 5, 10, 20 and 40 mm, respectively, at a firing distance of 10 m and at an inclination angle of 0° (i.e. pellet trajectory was perpendicular to the bone face). As expected, the observations show that the smaller the depth of gelatin, the more deformation of the pellet there is. Pellet 1 was completely deformed and fragmented (Fig. 9) whereas pellet 8 was deformed mainly around the head of the pellet (Fig. 10). By comparing the dimensions of the pellets, the amount of compression occurring between pellets can be partially quantified. Pellet 1 was recovered as three small pieces which had an average height of <1 mm; pellets 2 and 8 had a height of 3 mm and impact faces with dimensions of 10 mm × 11 mm; and pellet 3 had a height of 4 mm and an impact face of 9 mm × 10 mm.

3.10.2. Effect of bone angle

Pellets 4, 5, and 6 were fired at bones mounted at different angles in gelatin of 25°, 50° and 75° to the firing line, respectively. The firing distance was 10 m and the bone depth was 20 mm. Table 3 shows that the smaller the mounting angle (i.e. the more direct the impact) the more deformation there is. Bones mounted at 25° have the tendency to stop the pellet rather than deflecting it, causing more damage to the pellet and the surrounding gel. Also, as may be expected, an increase in the mounting angle increases the

Table 3
Test firing conditions for bone in gel.

Test	Bone depth (mm)	Angle (°)	Firing range (m)	Pellet	Pellet dimensions after impact (mm)		
					Width	Length	Height
	5	0	10	Huntsman	2.5	3.5	<1[a]
2	10	0	10	Huntsman	11	10	3
7	20	0	5	Huntsman	10	11	3.5
8	20	0	10	Huntsman	11	10	3
9	20	0	15	Huntsman	10	9	4
3	40	0	10	Huntsman	10	9	4
10	10	25	10	Harrier	6	10	6
4	20	25	10	Huntsman	11	11	3
13	30	25	10	Harrier	8	7	4
11	10	50	10	Harrier	7	3	4.5
5	20	50	10	Huntsman	7	3	9
14	30	50	10	Harrier	5.5	5.5	7
12	10	75	10	Harrier	8.5	9	3.5
6	20	75	10	Huntsman	Pellet ejected from gel		
15	30	75	10	Harrier	5.5	4	7

[a] Pellet completely deformed and only three small fragments retained.

Fig. 9. Damage to pellet with bone embedded 5 mm into gel.

deflection distance travelled. Pellet 5 (50°) travelled a further 60 mm after deflection whereas pellet 4 (25°) only travelled a further 10 mm. Pellet 6 (75°) was expelled completely from the gel after a deflection of about 40–50 mm in the gelatin. As can be seen in Fig. 11, pellet 5 has been deformed on one side only whereas pellet 4 was deformed all round. The deformation in pellet 5 caused the pellet to follow a curved trajectory upon deflection rather than the expected straight line.

3.10.3. Effect of firing distance

Pellets 7, 8, and 9 were shot at varying distances of 5, 10 and 15 m, respectively, at a bone depth of 20 mm and a mounting angle of 0°. It would be expected that as the firing distance decreases, the deformation would increase. This is true to an extent when comparing pellets 8 and 9, but the damage to pellet 7 is not as intense as that of pellet 8. Closer examination showed that this bone was mounted at a slight angle, in the region of about 3–5°, which may have caused less damage to the pellet than it would of at 0°.

3.10.4. Effect of bone angle and bone depth combined

Pellets 4, 5, and 6 were fired at bones at a depth of 20 mm in gelatin and at 25°, 50° and 75°, respectively to the firing line. Pellets 10, 11, and 12 were fired at bones mounted at the same angles (25°, 50° and 75°, respectively) and at a bone depth of 10 mm, whilst pellets 13, 14, and 15 were fired at a bone depth of 30 mm and similar angles. All shots were fired at 10 m range and this data allows a comparison of bones mounted at 25°, 50°, and 75° in gelatin at depths of 10, 20, and 30 mm.

Pellets 4, 5, and 6 were BSA Huntsman which were a pointed tip variety of pellet, and Pellets 10–15 were a round nosed Webley Harrier variety, so the first set of data are not directly comparable with the second two sets, but they still indicate the trends. As can be seen from the data in Table 3, the deeper the bone is mounted in the gelatin, the less damage is caused to the pellet. At 25° it can be seen that pellet 10 at 10 mm depth has been deformed the most, with a residual height of 2.3 mm, whilst pellet 13 at 30 mm depth, has been deformed the least with a height of 5 mm. The same is also true for angles of 50° and 75°, with more deformation occurring in shallower depths of gels. It would be expected that a deeper depth of gelatin would slow down the pellet and absorb the energy from the pellets, resulting in a lower impact energy. The most damage to the pellet occurs with the smaller angles (direct impact) rather than the larger angles (oblique impact). At 75° the pellet is deflected with less pellet damage being caused, whereas at 25°, the pellet has a tendency to be stopped upon impact rather than being deflected.

Fig. 10. Damage to pellet with bone embedded 20 mm into gel.

Fig. 11. Damage to pellet with bone embedded 20 mm into gel and at an angle of 25 degrees.

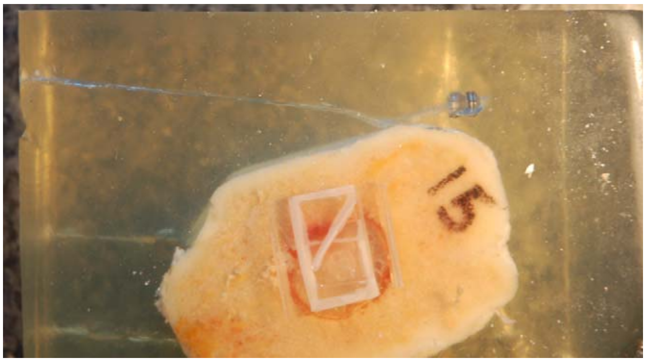

Fig. 12. Track of pellet in gel showing displacement near the bone.

Some of the pellets hit the bone at a corner or an edge which resulted in some interesting observations, as shown in Fig. 12. As the pellet approaches the corner or edge of the bone in a straight line, it seems to curve in towards the bone at a distance of about 5 mm from the bone. This is unusual as most of the other shots impacted the bone along a straight line. Reasons for this are unknown, but could possibly be due to gel displacement affecting the trajectory of the pellet as it approaches the bone and the gel in the area ahead of the pellet being less elastic due to the nearby presence of the bone.

3.11. Penetration and energy on impact

It would be useful to be able to estimate the energy on impact in order to better understand the damage that may occur. Various models have been developed for bullet and shot trajectories in different media, but the situation is complex for a number of reasons. Firstly there is a debate whether energy or momentum is important in inflicting injury [19]. Cross-sectional density and drag coefficient also play a part in a pellet's behaviour and in the damage generated. Even applying conventional physical equations may not be straightforward. For example Stokes and Newton's theories can predict the viscous drag on particles moving through a fluid at 'normal' velocities, but at pellet velocities of 170 ms^{-1} (550 fps) other factors need to be considered. In the case of a pellet travelling in air there is the compression of the air ahead of the pellet and air density and viscosity will be different from standard state conditions. Similarly, a pellet fired into water or into gel could be modelled by considering the viscous drag on the pellet, but this model assumes that the fluid has time to flow. The liquid or gel may behave in a similar manner to non-Newtonian fluids where behaviour depends on strain rate, and the material flows as a fluid under low strain rate but behaves like a solid at high strain rates. The liquid or gel would then need to be considered as a plastic solid restraining the pellet. Mathematical calculation of viscous drag on the pellets in water and in gel was carried out and viscous drag did not appear to adequately explain stopping distances in gel or water.

An additional factor to be considered will be the impulse (force $\times$ time) occurring at the phase boundary. This phenomenon is observed in stone skimming where water appears to behave as a solid due to the short impact time on the surface.

The pellet leaves the rifle with an initial kinetic energy and some energy will be lost by air resistance, some by the impulse at the phase boundary, and more energy will be lost by interaction with the gel. At impact with the bone some of the remaining energy will be lost as damage to the bone and the pellet, and the remaining energy is lost by further interaction of pellet fragments with the gel. If the gel is behaving as a plastic it will deform (i.e. go from elastic to plastic behaviour) once the yield strength is exceeded and this will normally be a constant value. For an initial approximation the energy loss in the gel could then be equated to the work done, i.e. force times distance moved. By taking a constant retarding force (determined by the yield strength) and distance (determined by the penetration) an approximation of the energy loss can be estimated. Yield strength is related to the Bloom value but it also depends on the gel concentration, and a linear dependence on concentration above 15% was noted in Section 3.4.

The energy at the point of impact with the bone could therefore be estimated by assuming this linear relationship and comparing a shot fired against a bone with one fired into gel but not striking the bone.

In tests 5, 6 and 8, the bone was placed at 20 mm depth and firing was done from 10 m range. At 0° the pellet rebounded 5 mm, at 50° it travelled a further 50 mm and at 75° it was expelled after a further 40–50 mm in gel. The muzzle energy was measured as 8.5 J and in Section 3.7 a 13% reduction in gel penetration was noted for a 5 m distance in air (going from a range of 5–10 m). Assuming a 25% energy loss before impact from a 10 m range means that the pellet would have 6.4 J to dissipate in the gel. In the earlier phase pellets were fired under similar conditions (10% concentration, 250 Bloom, muzzle velocity of 130 ms^{-1}, range 10 m) and the penetration was 139 mm. Assuming a linear relationship for energy absorption with distance (constant retarding force), this suggests that 5.2 J were absorbed by deformation of the pellet and 1.2 J by the 25 mm of gel. At 50° the pellet travelled 70 mm in the gel suggesting the energy absorbed by impact would need to be 3.2 J. This difference in energy dissipation may be expected to be seen in the deformation of the pellet and this is shown in Table 3 test firings 5 and 8. An impact energy of 6.4 J would need to correspond to a constant restraining force of 46.0 kN over 0.139 m penetration.

The model is tentative and requires further work to see whether the calculated opposing force corresponds quantitatively with the physical properties of the gel and whether the energy absorbed on impact corresponds with the damage caused to the pellet.

4. Conclusions

This study has highlighted a number of issues with respect to air weapons tested in ballistic gel, and a modified test procedure may be required for air weapons. At low powers the currently accepted procedures do not appear to give good differentiation of pellet penetration. Air pellets have low cross-sectional density but appear to penetrate further than might be expected. Gel Bloom strength is only a partial guide to suitability for ballistic testing.

A pellet fired into ballistic gel and hitting a plastic wall underwent 180° inversion within three pellet lengths and this pattern of motion may be worth studying further by high speed photography to determine local temporary and permanent disruption of the gel around the impact site.

Pointed pellets penetrate further than rounded pellets by 11–53% meaning that a pointed pellet fired at 16.3 J (the legal UK limit) may do as much damage as a rounded pellet fired from a weapon that is above the legal limit. Power alone therefore may not be an effective criterion for predicting penetration, and hence injury, and further investigation is required to determine whether there is a safe limit for air weapons.

Computed tomography has been used to examine the behaviour of air rifle pellets on impact with bone in ballistic gel. The technique allows examination of bone and pellet damage in situ in 3D. In the present tests using a cow femur no bone damage was observed. However, serious damage occurred to the pellets and fragmentation could occur with the pellet fragments ricocheting. The presence of lead fragments and these additional trajectories could result in more serious injury to soft tissues than might initially be expected. For pellets fired at an angle to the bone

the pellet trajectory sometimes curved towards the bone, potentially affecting the localised damage caused by the pellet.

The effect of gel depth and bone angle to the pellet trajectory have been investigated. Greater gel depth reduces the impact energy of the pellet, and impact angle affects the deflection of the pellet and its deformation and fragmentation. Material behaviour at the high strain rates may need to be considered and a semi-quantitative model has been proposed of energy dissipation in gel and bone. It is postulated that a constant retarding force is applied through the yield or rupture of the gel and this would account for the correlation between gel concentration and penetration. This model needs further development. but could be useful in predicting pellet behaviour in gel-bone conditions designed to simulate human injuries.

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